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Research Article

On the road chasing the elusive solution: Evaluating combined deterrents for safer wildlife road crossings

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Abstract

The negative impact of roads and railways on nature and landscape is a well-known fact. The construction of linear infrastructure leads to the fragmentation of previously functional parts of the landscape, direct loss and encroachment of habitats and disruption of the water regime in the surrounding area. It also causes loss of balance in the ecological functions of the landscape, including interruption of its movement permeability for animals. Among the most visible negative effects are animal-vehicle collisions, which can affect the viability of local populations of both common and endangered species. We tested the effectiveness of two types of animal deterrents that combine optical-acoustic and optical-olfactory stimuli and were designed to decrease the number of roadkills. We performed a Before-After continuous cadaver monitoring experiment (for 21 months before treatment and 18 months after treatment) on seven test sections of roads (with total length of 18.6 km), supplemented by Control-Impact data from 88 km of control road sections. Our results indicate that the tested deterrents did not have a statistically significant effect in reducing mortality. These findings highlight the need for additional ethological investigations to determine whether animals respond to the deterrent stimuli and should be carried out prior to any field testing. Robust, evidence-based field evaluations of mitigation measures are then necessary to ensure that only devices proven to effectively reduce animal–vehicle collisions, save lives, and prevent associated ecological and economic losses are implemented along roads.

Key words: Animal-vehicle collisions, Deer Deter, Hagopur Kombiset, road mortality

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Introduction

The negative impact of roads and railways on nature and landscape is a well-known fact (Trombulak and Frisell 2000; Burton et al. 2003). The construction of linear infrastructure leads to the fragmentation of previously functional parts of the landscape (Ceia-Hasse et al. 2018), direct loss and encroachment of species habitats (Kuipers et al. 2021; Remon et al. 2022), disruption of the water regime in the surrounding area (Jandová et al. 2020) and loss of balance in the ecological functions of the landscape (Barrientos et al. 2021), including

interruption of its movement permeability for animals (Forman and Alexander 1998; van der Ree et al. 2015; Papp et al. 2022; Botting et al. 2025). Hereinafter, movement is understood in the broad sense of the word and includes, for example, dispersal, daily activity (searching for food/mate), seasonal shifts, etc. In addition to the direct effects, there are also negative side effects such as light or noise pollution associated with road and rail traffic (Iuell et al. 2003).

Animal-vehicle collisions (AVC) are the most visible negative effects, which affect the survival of local populations of both common and endangered species (Fahrig and Rytwinski 2009; Rytwinski and Fahrig 2015; Hill et al. 2019; Moore et al. 2023). During a collision between a car and a larger species such as European deer (*Cervus elaphus* L.), European elk (*Alces alces* L.) or wild boar (*Sus scrofa* L.), damage to property, serious injury or even loss of life can occur (Bíl et al. 2025). According to Grilo et al. (2020), up to 194 million birds and 29 million mammals are killed on European roads annually. The number of collisions with ungulates is estimated at 5.1 million in Latin America (Medrano-Vizcaíno et al. 2022), 0.5 million in Europe and 1.5 million in the USA (Langbein et al. 2011).

In 2024, police in the Czech Republic dealt with 9,317 traffic accidents caused by collisions with wildlife or domestic animals, which is 10.1% of the total number of accidents. Insurance companies paid out more than 442 million CZK (ca 18.1 million EUR) in 2024 and the number of collisions has been steadily increasing over the long term (Generali Česká pojišťovna and CDV 2024).

Past research has found that hotspots or so-called blackspots can be identified at a local scale (Bíl et al. 2013; Husek et al. 2026). These represent individual sections of roads with a higher frequency of AVC compared to the rest of the road network and a higher risk for drivers in terms of safety (Favilli et al. 2018). At the same time, it has been proven that hotspots accumulate a higher frequency of mortality even though the length of these sections is relatively small compared to the total length of the roads. Therefore, targeted mitigation measures should be directed to these sections to reduce AVC (Bíl et al. 2019; Moulherat et al. 2024).

The use of more costly measures, such as fencing or wildlife-crossing structures, is justified for main roads (with higher traffic volumes). The construction of a fence must necessarily be accompanied by the construction of a sufficient number of, and well designed mitigation structures such as underpasses or overpasses to achieve higher effectiveness in reducing road-kills (Rytwinski et al. 2016) and preserving landscape connectivity (Karlson et al. 2017). On the other hand, the use of artificial deterrents (e.g. warning reflectors, odour repellents, detection systems etc.), which are less costly, is recommended for secondary roads with low and irregular traffic (Putman 1997; Putman and Langbein 2024). However, the effectiveness of these mitigation measures were questionable (Rytwinski et al. 2016). Therefore, qualified testing of effectiveness should always precede any large-scale implementation of preventive measures (Rytwinski et al. 2015; van der Ree et al. 2015).

Various measures have been tested on lower class roads to prevent or at least reduce the risk of AVCs. Odour repellents have been proven ineffective as they did not reduce animal mortality (Elmeros et al. 2011; Putman and Langbein 2024). Moreover, no clear effect of odour repellents on roe deer behaviour (Bíl et al. 2020) or wild boar behaviour (Faltusová et al. 2024) has been noticed. On the contrary, several studies pointed out possible short-term positive effect of odour repellents, leading to mortality reductions in the range of tens of percent (Andreassen et al. 2005; Kušta et al. 2015; Bíl et al. 2018; Bíl et al. 2024).

Another type of mitigation measure that has been studied on roads is the wildlife warning reflector. Brieger et al. (2016) reanalysed AVC data from 53 references and concluded that light-reflecting devices did not significantly reduce the number of animal-vehicle collisions. Another comprehensive review done by Benten et al. (2018a) reported that of the 62 studies examined, most find wildlife warning reflectors to be ineffective (n = 19), or even that they (marginally) increase mortality when road sections are fitted with them (n = 26). Other publications referenced in this study reported no effect (n = 7) while twenty studies indicated a decreasing trend. A study conducted by Benten et al. (2018b) concluded that wildlife warning reflectors are not an effective tool for mitigating wildlife-vehicle collisions on roads. Benten et al. (2019) reported ungulates to be more likely to leave the road side area with reflectors present, however, this effect lasted only temporarily for 16.5 days.

Brieger et al. (2017) tested the effect of blue semi-circular reflectors on roe deer behaviour both in an experimental setting and in the road proximity and did not observe a significant change in roe deer behaviour. The study conducted by Jasińska et al. (2022) indicated that wildlife warning reflectors were not effective to modify animal behaviour and to reduce risk of train collisions. Acoustic deterrents were tested in a recent study (Al Sayegh Petkovšek et. al. 2025) who reported their inefficiency to decrease road-kill after installation. The acoustic devices which emit natural frightening calls of animals appear to be more effective in reducing risk of animal–train collision (Babińska-Werka et al. 2015).

Animals have evolved sensory systems tuned to specific frequency ranges and visual spectra. Devices that emit light wavelengths or sounds outside a target species' perceptual range may be undetectable or meaningless to them. This limits deterrent efficacy. For example, artificial light reflectors on roads often fail because wildlife cannot perceive the light adequately, it's masked by other illumination, or is not salient against background visual noise. Light and sound deterrents for wildlife-vehicle collisions often fail because animals rapidly habituate to predictable, non-threatening stimuli, a core principle in behavioural ecology known as stimulus habituation or sensory adaptation. This undermines their effectiveness in altering road-crossing decisions, as animals learn to ignore cues that lack consistent negative reinforcement (Ujvári et al. 1998; Ujvári et al. 2004; D'Angelo et al. 2006; Rutherford et al. 2025). Moreover, road-deployed wildlife deterrents, such as reflectors, acoustic devices, and lights, are frequently installed to curb animal-vehicle collisions without prior behavioral validation rooted in ethology the study of natural animal behavior. This leads to widespread deployment of unproven measures, where animals often fail to react meaningfully to stimuli, resulting in negative outcomes that are hard to interpret due to lacking baseline ethological data (Brieger et al. 2022).

The aim of the study was to determine the effectiveness of two portable deterrent device types fitted along blackspot road sections in reducing collisions with mammals. We used the BACI (Before-After-Control-Impact) experimental design as recommended by Roedenbeck (2007) and Brieger at al. (2016). We tested two deterrent types which combine two different stimuli 1) optical-acoustic Deer Deter and 2) optical-olfactory Hagopur Kombiset, whose effectiveness has not yet been verified or published in the past. We assumed that the combination of different stimuli used together in each deterrent would be more effective in reducing mortality than using separate stimuli. We evaluated

data from three sources (our own, hunters and Police), which we consider to be an above-standard approach from a methodological point of view. Another benefit of our study is the above-standard length of AVC data collection 21 months before and 18 months after detterents installation.

Methodology

Study area and road sections' characteristics

Our study has been carried out on roads in the Vysočina Region located in the central part of the Czech Republic. A large part of the region is made up of the Bohemian-Moravian Highlands, which forms the natural border between the historical lands of Bohemia and Moravia. The road network in the overall length of 4,964.7 km consists of a 92.5 km section of motorway D1, which divides the region into southern and northern parts, 423.1 km of national roads (recognized as Class I roads according to the Czech legislation) and 4,448.9 km of roads with interregional and local importance designated as Class II and Class III roads (Regional Administration and Maintenance of Roads in Vysočina Region 2025).

The Vysočina Region has the highest proportion of accidents involving collisions with animals in the Czech Republic. This type of accident accounted for 26.28% of all accidents in this region in 2024, on average 3,947 accidents per year happen in this region (Portalnehod 2025).

Seven road sections with a total length of 18.6 km (11.4 km of Class I roads, 7.2 km of Class II roads) were selected for the AVC monitoring before and after installation of the wildlife deterrents. Most of the sections are standard two-lane roads without directional separation; just part of section 2 and part of section 7 are roads with an additional lane for overtaking slow vehicles, making it a three-lane road. None of the sections is included in the European TEN-T network.

According to the hunting bag statistics, 407/421 red deers, 1,488/1,790 fallow deers (*Dama dama* L.), 807/917 mouflons (*Ovis orientalis musimon*, Pallas), 12,772/14,797 roe deers (*Capreolus capreolus*, L.), 17,308/20,519 wild boars and 4,414/4,875 European brown hares (*Lepus europaeus*, Pallas) were hunted in the Vysočina Region during the periods of April 1, 2022 - March 31, 2023 (numbers before slash) and April 1, 2023 - March 31, 2024 (numbers after slash) (Czech Statistical Office 2025).

Wildlife warning deterrents

Deer Deter 430 Electronic wildlife guard (D)

The first tested deterrent was Deer Deter DD430 Generation 5 from iPTE Traffic Solutions, manufactured in Austria. It is a combined optical-acoustic device activated by the internal daylight sensor from dusk during the night until dawn. It is equipped with a built-in ambient light sensor with an activation threshold 150 Lux, vehicle headlamp detection (300–500 m) and solar cells optimized for low light conditions. Its dimensions are 160 mm (height) x 74 mm (width) x 48 mm (depth) and it weighs 100 grams. After the device activation by the car headlamp, the Royal blue (480 nm) and amber (480 nm) LED flashes and at the same time a high frequency acoustic alert is emitted. We used "standard warning sound" (3.5 to 6.5 kHz)

in the vast majority of devices. High alert sound (7 to 13 kHz) was employed in several exceptional cases where the device was adjacent to a residential building.

Each Deer Deter unit was installed on a triangular delineator post at a distance of 50 metres along both sides of the road. New triangular posts had to be installed in sections that were originally equipped with flat posts. At the same time, in road sections with guardrails, deterrents were mounted on special attachments above the guardrails. The installation was conducted either by the Czech Road and Motorway Directorate (first class road sections number 1, 2, 4 and 7) or by the Regional Administration and Maintenance of Roads in Vysočina Region (second class road sections number 3, 5 and 6).

Hagopur Kombiset, Multiwarn - Wildlife Protector (K)

The second tested deterrent was Hagopur Kombiset (Multiwarn - Wildlife Protector), which is a combined optical-olphactory device consisting of two parts. One part is formed by eight multi-coloured (light blue, dark blue, green, white) honeycomb platelets (Multi-Wildschutz-Warner) and the second upper part consists of a semi-circular shaped chamber with a sponge inside, which is used for the application of odour concentrate (Duftzaun-konzentrat from Hagopur AG, Landsberg, Germany). Around the chamber there is a blue reflective foil with a high degree of reflection. Its dimensions are 170 mm (height) x 70 mm (width) x 35 mm (depth) and it weighs 80 grams.

Each deterrent was installed in the same way as the deterrent type Deer Deter. The device was mounted on a triangular delineator post at a distance of 50 metres along both sides of the road. The odour concentrate spray was applied to each device with three squirts into the sponge at the top of the device. Renewal of the odour concentrate was carried out every third month, as recommended by the manufacturer Motzener Kunststoff- und Gummiverarbeitung Inc. (Multi Wildschutz Warner 2025).

Experimental design and data collection

Animal vehicle collision (AVC) monitoring was carried out on seven test sections and seven control sections of first and second class two-lane roads (henceforth ‘road section’) in the Czech-Moravian Highlands - Vysočina Region between the towns of Havlíčkův Brod, Pelhřimov and Jihlava (Fig. 1).

The monitoring started in March 2022 and for the purpose of this study, data collection was completed in May 2025. The AVC data collection before the installation of the deterrents was conducted from March 1, 2022 to November 30, 2023 (21 months). The AVC data collection after treatment i.e. after the installation of the deterrents was conducted from December 1, 2023 to May 31, 2025 (18 months). Mammal species listed below that died after colliding with a vehicle were recorded during the monitoring. For each animal, the following information was recorded: species, photo, date and GPS coordinates. The following species were recorded: roe deer, fallow deer, wild boar, red fox (*Vulpes vulpes*, L.), European brown hare and stone marten (*Martes martes*, L.). In one third of the cases it was not possible to identify the marten species because of the high degree of damage to the carcass, so it is possible that beech marten (*Martes foina*, von Schreber) was among them (martens evaluated altogether).

Seven test road sections with a total length of 18.6 km were selected for AVC monitoring (sections 1–7 with before and after experimental treatment). The deterrent Deer Deter was installed on two first and two second class road sections, while the deterrent Hagopur Kombiset was installed on other two first road class sections and one second class road section (see Suppl. material 1). All these road sections were checked at weekly intervals by walking back and forth on both sides of the road (for the whole period by the same person). We carried out checks of the functionality of the Deer Deter (only after dark, when it is in its operational mode). Mechanically broken or missing devices were immediately replaced.

The seven test road sections were selected based on known data on increased AVC. Our selected study sections included locations with the highest collision density or locations where AVCs are concentrated (so called AVC hotspots), calculated using the KDE+ method (Bíl et al. 2013). Data on mortality and location of traffic collision clusters are available at www.srazenazver.cz.

In addition, AVC data were also recorded on 7 control road sections (17, 21, 30, 43, 52, 65, 76) with a total length of 88 km, which were adjacent to the monitored sections. Minimum length of a control section which was adjacent to the test section was 500 metres (after test section 3). These checks were intended to detect possible edge effect that might occur just behind the test section fitted with deterrents. Moreover, the control sections were 4.7× longer and were situated between test sections adjoining them (Fig. 1). This experimental design was chosen so we could record any long-term AVC changes in the widest possible area where the selected roads were located. At the same time, we took advantage of the fact that we had additional AVC data from the Police database for the entire study area. Therefore, we planned the most effective method of collecting our own data from the control sections (Livingston 2019).

Animal mortality on the control road sections was recorded using slowly driven motorized vehicles (scooter or car in winter time) at weekly intervals from March 1, 2022 to May 31, 2025 (own monitoring on control sections). Data collection was also conducted by the same person, similarly to the case of monitoring on test (before-after) road sections. The differing data collection methodology may have affected the detectability of dead animals, which could lead to systematic bias favouring the test sections; however, in a before-after type of monitoring, this bias is minimal due to the consistency of data collection methods within sections throughout the trial.

Another source of data on AVC from test sections was obtained from local hunting association managers belonging to 11 hunting grounds. According to the Hunting Act, the evidence and removal of road-killed game species falls within the competence of the hunting ground users.

The database of collisions with wildlife (mainly roe deer, fallow deer and wild boar) managed by the Police (“police data”) was used as the last additional source of AVC data from both the test and the control road sections. We are aware that police data do not include all animal–vehicle accidents. However, we assumed that this underreporting was evenly distributed in the study area, thus excluding spatial bias (Snow et al. 2015).

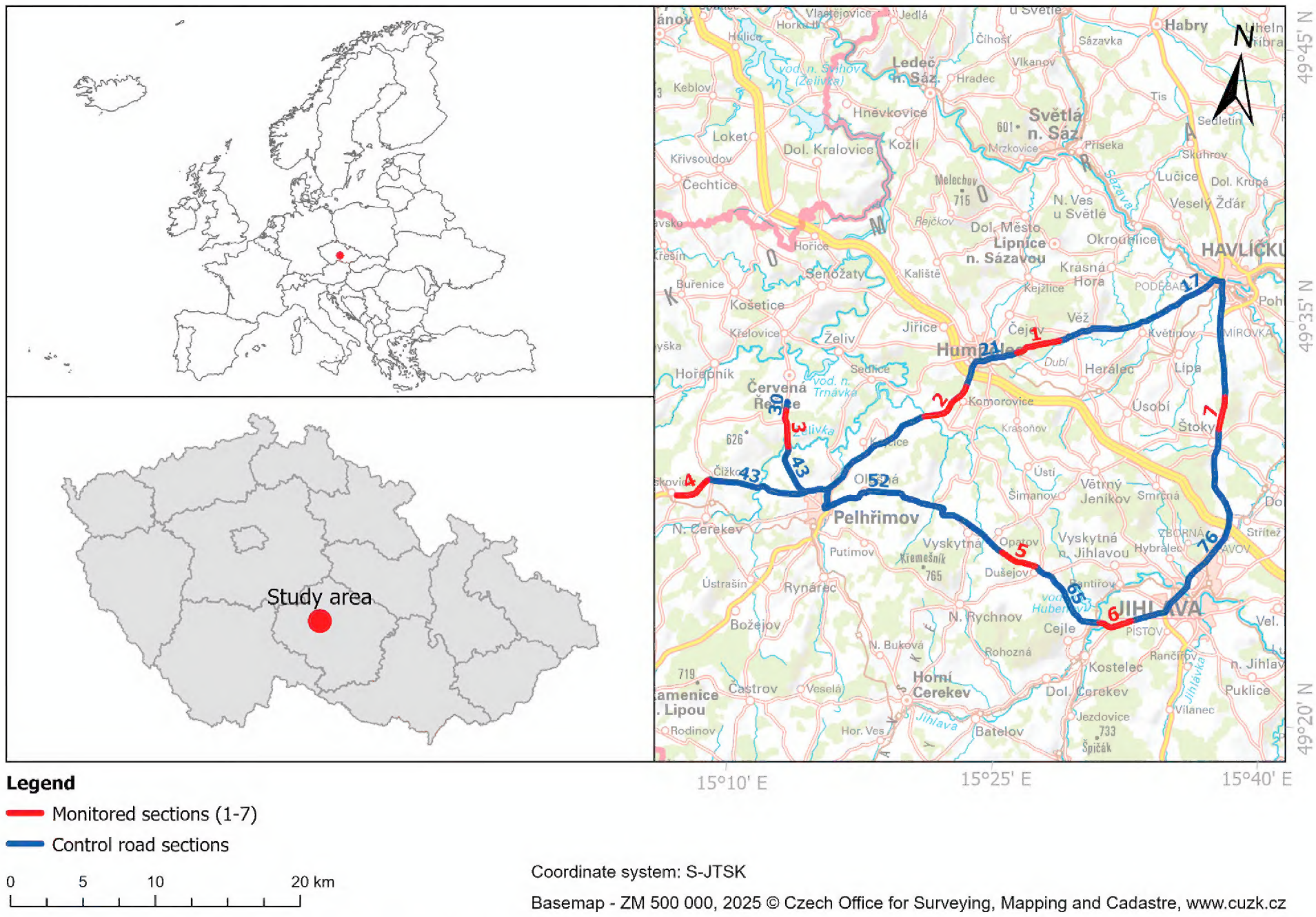

Figure 1. Overview map with the location of test road sections 1–7 (in red) and control road sections (in blue) in the Vysočina Region, the Czech Republic.

Real traffic intensity on test road sections

A one-week traffic volume monitoring was carried out on six monitored road sections (1–6) in May and November 2023 and 2024. These periods of the year were chosen based on the highest migration of the roe deer and the wild boar, as well as the peak in road mortality rates, which occur during these periods (Bíl et al. 2018).

Mobile automatic traffic counters were employed to carry out traffic surveys in a continuous manner in each locality. The length of each measurement was at least 168 hours, consisting of 5 working days, one Saturday and one Sunday. The vehicle detection device Sierzega SR4 recorded all vehicles passing on the road. The detector of this device – radar – works on the basis of the Doppler effect. Information on each vehicle was stored, including direction, date + time, vehicle category and travel speed. Devices were mounted on road sign poles in a suitable place (straight section of road, no crossroads or speed bumps). In the seventh section, data from the automatic stationary traffic counter provided by the Roads and Motorways Directorate were used for evaluation.

Traffic intensity is presented here in the form of a general traffic-engineering characteristic called Annual Average Daily Traffic (AADT) (Bartuška et al. 2016). It is expressed as the number of vehicles per 24 hours on a given section of a road and represents the average value for all days of the year, i.e., weekends

or lower periods (winter). The measured real traffic intensity was recalculated to AADT with the coefficients from the official methodology approved by the Ministry of Transport (Bartoš 2018).

Statistical design and analysis

Data were collected continuously and divided into four time periods: 03/2022–12/2022, 01/2023–11/2023, 12/2023–12/2024, and 01/2025–05/2025. The lengths of the individual periods differ due to the project starting in March 2022, the installation of deterrents in December 2023, and the end of monitoring in May 2025. For these reasons, data were not collected over equally long time intervals, which limits direct comparability between periods and may affect the statistical power of the tests.

For simplicity, the individual periods are further labelled according to the calendar year that predominates in the given period. The periods of the years 2022 and 2023 are referred to as "before installation," and the periods of the years 2024 and 2025 as "after installation" of the deterrents. When evaluating the results and especially when interpreting them, the limitations arising from this project timeline are taken into account.

Because the observation periods differ in length, outcome measures were annualized to ensure comparability. This procedure implicitly assumes a relatively stable rate within each aggregated period. If strong seasonal variation were present (e.g., spring peaks in mortality), annualization could introduce measurement bias. However, both aggregated comparison periods (03/2022–11/2023 and 12/2023–05/2025) span multiple seasons, including spring and autumn months, which mitigates potential seasonal distortions. Therefore, while unequal period lengths may affect statistical precision, systematic seasonal bias in the pre–post comparison is unlikely.

The monitored sections were divided into three groups: four sections where the Deer Deter device was installed, three sections equipped with the Hagopur Kombiset device, and seven sections without the installation of any deterrent.

For further analysis and clarity, these groups will be referred to as follows:

- D – sections with installed Deer Deter device
- K – sections with installed Hagopur Kombiset device
- C – control sections without deterrent installation

These labels will be used throughout the text, graphs and tables. Data were obtained from three sources. The first source was our own field collection (Own) on test and control sections. The second data source was records from local hunting associations (Hunter). These data were available exclusively for the test sections and not for the control sections. The third source was data from the Police of the Czech Republic (Police), which include information on reported collisions with wildlife. These data are available for all types of sections (test and control).

Although the datasets originate from different sources, each source collected data independently using its own methodology. The datasets were analyzed both separately and in combined models to assess robustness. Nevertheless, differences in reporting practices and detection probability across sources may introduce heterogeneity that is not fully captured by the statistical models.

To allow better comparison of the obtained data, which are only available as aggregated values for individual time periods, data transformation was performed. Due to the varying lengths of the periods, values were first recalculated to average annual values to compare the intensity of the phenomenon over time. Subsequently, they were adjusted for the lengths of the monitored sections so that the resulting values express wildlife mortality per one kilometre per year. This method ensures that the values are directly comparable regardless of section length or monitoring period duration.

To evaluate the effectiveness of the deterrents, a metric was calculated from the transformed values using the BACI method. This method allows comparison of changes in the number of wildlife collisions between test and control sections before and after the installation of deterrents.

To calculate the effect size, the method described in Brieger et al. (2016) was used, based on the standardized mean difference according to Hedges and Olkin (1985). In the original study, the effect size was calculated as the difference between the means of groups with and without device installation (CI design), where Y_1 denoted sections with installation and Y_2 those without installation.

In our study, however, a BA design was used, comparing the situation on individual sections before and after deterrent installation. In this context, the variable definitions were modified as follows:

- Y_1 represents the average number of animal collisions before deterrent installation
- Y_2 represents the average number of animal collisions after deterrent installation

This modification means that a negative effect size value ($d < 0$) indicates a decrease in animal mortality after installation, i.e., a positive effect of the deterrents on reducing collision numbers.

This redefinition aligns with the study's aim, which is not a direct comparison of different sections among themselves (due to different data collection methodologies), but an assessment of changes over time within individual sections.

The formula used is:

$$d = \frac{Y_2 - Y_1}{\sqrt{\frac{(n_1-1)\cdot s_1^2+(n_2-1)\cdot s_2^2}{n_1+n_2-2}}}$$

where:

Y_1 = average number of animal collisions in periods before deterrent installation

Y_2 = average number of animal collisions in periods after deterrent installation

n_1 = number of time units in sections before deterrent installation

n_2 = number of time units in sections after deterrent installation

s_1 = standard deviation in periods before deterrent installation

s_2 = standard deviation in periods after deterrent installation

This metric allows expressing effect size independently of units and thus facilitates comparison among sections.

The obtained effect size values were statistically evaluated to identify significant differences both between types of sections and within groups comparing

periods before and after deterrent installation. Various statistical methods were used to verify assumptions and perform testing.

First, data normality was analyzed. A two-sample t-test was used for testing differences between two independent groups. Changes over time within one group (before vs. after installation) were assessed by a paired t-test.

As a complement to the primary analysis using the paired t-test, a non-parametric evaluation of changes between the periods before and after the installation of deterrent devices was also conducted. The objective was to assess the robustness of the observed results and to determine whether a consistent decrease occurred across individual segments, even without assuming data normality.

Due to the very small sample size in some groups, common non-parametric methods such as the Wilcoxon signed-rank test did not yield reliable results under these conditions and often failed to reject the null hypothesis, even when all observed changes were in the same direction.

For this reason, the sign test was employed as a suitable non-parametric alternative. This test compares the direction of change in paired observations (before–after) regardless of the magnitude of the difference and, unlike most other tests, allows for exact evaluation even with very small samples ($n \in [3,7]$). It was therefore used as a supplementary method to verify whether the observed reduction in animal mortality in individual road sections was systematic and unlikely to be attributed to random variation.

For multi-group comparisons, analysis of variance (ANOVA) was used. Due to the small number of observations, deviations from normal distribution could not be reliably detected - thus, the result may only indicate apparent normality due to low test power. Therefore, results of parametric tests (e.g., t-tests or ANOVA) should be interpreted cautiously and in the context of the overall data characteristics. Where robustness assumptions were not met, the nonparametric Mann–Whitney U test was used as an alternative method. In addition, given the small sample sizes in some groups (n = 3–7), the statistical power of the tests is limited; therefore, non-significant findings should not be interpreted as evidence of absence of an effect. The relatively wide confidence intervals further highlight the limited precision of the estimates and the associated uncertainty.

Further, regression analysis was performed to assess the influence of installed deterrent types on effect size. The model included two binary (indicator) variables representing the type of device used – Deter (D) and Kombiset (K):

$$d_i = \beta_0 + \beta_1 D_\mathrm{i} + \beta_2 K_\mathrm{i} + \varepsilon_i$$

where:

d_i = effect size on the iii-th section

D_i = binary variable indicating use of Deter deterrent (1 = yes, 0 = no)

K_i = binary variable indicating use of Kombiset deterrent (1 = yes, 0 = no)

β_0 = intercept (average value for control sections)

β_1, β_2 = estimated effects of individual deterrent types compared to the control group

ε_i = model error

This model allows estimation of how the effectiveness of individual device types differs from control sections without installation.

The evaluation was conducted using several different approaches. We assessed our own data separately, then combined our own data with police records (without data from hunting associations due to their absence in control sections), and also the combined total of all data.

The analyses were therefore conducted using five different models.

- **Model 1** includes only data from field monitoring done by the authors (own data).
- **Model 2** combines own data with reports from the Police.
- **Model 3** includes all available sources: own data, hunting associations, and police reports.
- **Model 4** treats each data source as an independent sample, reflecting the fact that data were collected separately and independently. This approach increases the sample size and allows for better comparison within the B-A design.
- **Model 5** addresses the fact that data from hunting associations are not available for control segments. It modifies Model 4 by excluding this data also from treated segments to ensure comparability.

We are aware that Model 4, which treats each data source as a separate analytical unit, may raise concerns regarding potential dependence, as the sources refer to the same physical road segments. Although the datasets were collected independently and do not represent duplicated observations of identical events, they may still share contextual influences related to the same location. For this reason, Model 5 was introduced as a more conservative specification. In Model 5, data from hunting associations—unavailable for control segments—are excluded also from treated segments to ensure structural comparability and reduce potential imbalance introduced by heterogeneous source availability. The comparison between Models 4 and 5 allows us to assess whether the conclusions remain robust under stricter assumptions regarding data comparability and effective independence. Another approach was to work with three independent datasets for each section, which increased the sample size and provided a more appropriate comparison for the Before–After design because the data collection methods differ between sources. Even within our own data, collection was not uniform across all sections (test versus control sections), and the data from hunting associations were even more heterogeneous due to varying approaches. However, it is important to note that for each data group and specific road section, the data collection method remained consistent throughout the entire study period.

To assess the potential influence of traffic intensity on wildlife mortality, we applied both the Pearson correlation coefficient and the Spearman rank correlation coefficient. Pearson's r was used to evaluate the linear relationship between traffic volume and various mortality metrics, while Spearman's ρ served as a non-parametric alternative capturing potential monotonic relationships, which are more robust in the presence of non-linearity or outliers.

Correlations were evaluated both for the dataset as a whole and separately by section type (Deter, Kombiset) and by data source (own monitoring, hunting associations, police). Control sections were excluded from this analysis due to the unavailability of traffic data.

The influence of traffic intensity on wildlife mortality was assessed using both Pearson's and Spearman's correlation coefficients. Four correlation models were evaluated:

1. Animal mortality vs. traffic intensity – before installation of deterrents
2. Animal mortality vs. traffic intensity – after installation of deterrents
3. Effect size metric *d* vs. average traffic intensity
4. Percentage change in mortality vs. average traffic intensity

Control sections were excluded from this analysis, as no traffic intensity data were available for those road segments.

Results

Data overview

Table 1 presents transformed data for all monitored segments. Each segment is labelled with a numerical identifier and the type of deterrent installed, or the letter C which is a control segment without deterrent installation. Control segments are labeled so that their numerical designation matches the tested segments they are associated with, and are therefore also marked with two-digit numbers. Please note that for these control segments, data from hunting associations are not available and are thus always missing from this part of the dataset.

Before-After analysis

This section focuses on a Before–After (BA) analysis, comparing animal mortality rates before and after the installation of deterrent devices. The objective was to determine whether statistically significant changes in animal mortality occurred that could be linked to the use of these mitigation measures. Both parametric methods (paired t-test) and non-parametric methods (sign test) were used.

Table 1. Transformed wildlife mortality data by section type (D = Deter, K = Kombiset, C = Control) and data source (O = Own/H = Hunters/P = Police) in respective time periods (2022, 2023 before treatment; 2024, 2025 after treatment).

Section	2022	2023	2024	2025
1 - D	4/4.4/2	2.18/4.36/5.09	0.92/4.92/2.15	0/4/2.4
3 - D	3.36/3.84/2.4	2.62/4.36/1.31	1.48/9.97/2.95	1.92/11.52/1.92
6 - D	2.09/3.13/1.57	1.9/3.79/0.95	2.01/2.81/1.61	5.22/1.04/0
7 - D	2.73/11.45/3.27	4.46/10.91/4.96	2.1/6.71/4.2	1.09/6.55/2.18
2 - K	3.89/7.78/2.27	3.83/18.28/2.95	1.75/19.21/2.99	3.24/9.73/2.59
4 - K	6.72/13.92/0.96	5.67/20.95/3.05	2.22/19.94/4.43	2.88/14.4/0
5 - K	1/11/0.5	3.18/6.36/3.18	1.54/3.85/3.08	0/0/1
17 - C	0.88/-/0.88	0.74/-/1.41	0.45/-/1.22	0.58/-/0.58
21 - C	0.49/-/0.49	0/-/0.62	0.57/-/0	0/-/0
30 - C	0/-/51.02	7.42/-/56.12	0/-/28.91	0/-/24.49
43 - C	0.98/-/1.66	1.51/-/1.95	0.53/-/3.42	0.2/-/2.74
52 - C	1.68/-/0	2.15/-/0	2.16/-/1.11	0.99/-/0.39
65 - C	1.13/-/1.5	1.36/-/0.94	1.3/-/0.16	0/-/0
76 - C	1.06/-/1.41	0.71/-/0.94	0.27/-/0.35	0.42/-/0.14

The analysis is based on comparing the mean annual animal mortality per kilometre before and after the installation of the deterrents. The data and their graphical representation show a decrease in wildlife mortality after the installation of deterrents in most sections (Table 2, Fig. 2).

In addition, the relative percentage change was calculated to improve comparability between different road segments and data sources. The mean percentage change in animal mortality per kilometre between the periods before and after the installation of deterrents was estimated for each section type and is presented along with the standard deviation and 95% confidence interval ($\alpha = 0.05$). The values are reported separately for sections with Deter type (Table 3).

In control sections, wildlife mortality decreased by −45.5% (95% CI: −69.8 to −21.3), with a statistically significant effect. Sections treated with Kombiset deterrents showed a reduction of −22.0%, which was not statistically significant (95% CI includes zero). In Deter-treated sections, the mean change in mortality was −7.2% and was not statistically significant.

Table 2. Mean annual wildlife mortality per kilometre Before and After installation, by section type and data source.

	Deter	Kombiset	Control
Own	2.92/1.84	4.05/1.94	1.44/0.53
Hunters	5.78/5.94	13.05/11.19	–
Police	2.69/2.18	2.15/2.35	8.5/4.54

Table 3. Mean percentage change in animal mortality with 95% confidence intervals ($\alpha = 0.05$).

Section type	Mean change (%)	Std. deviation	95% CI lower	95% CI upper
Deter	-7.2435	68.832	-42.9279	28.4409
Kombiset	-21.9608	36.7994	-44.7709	0.8493
Control	-45.5207	49.018	-69.7511	-21.2902

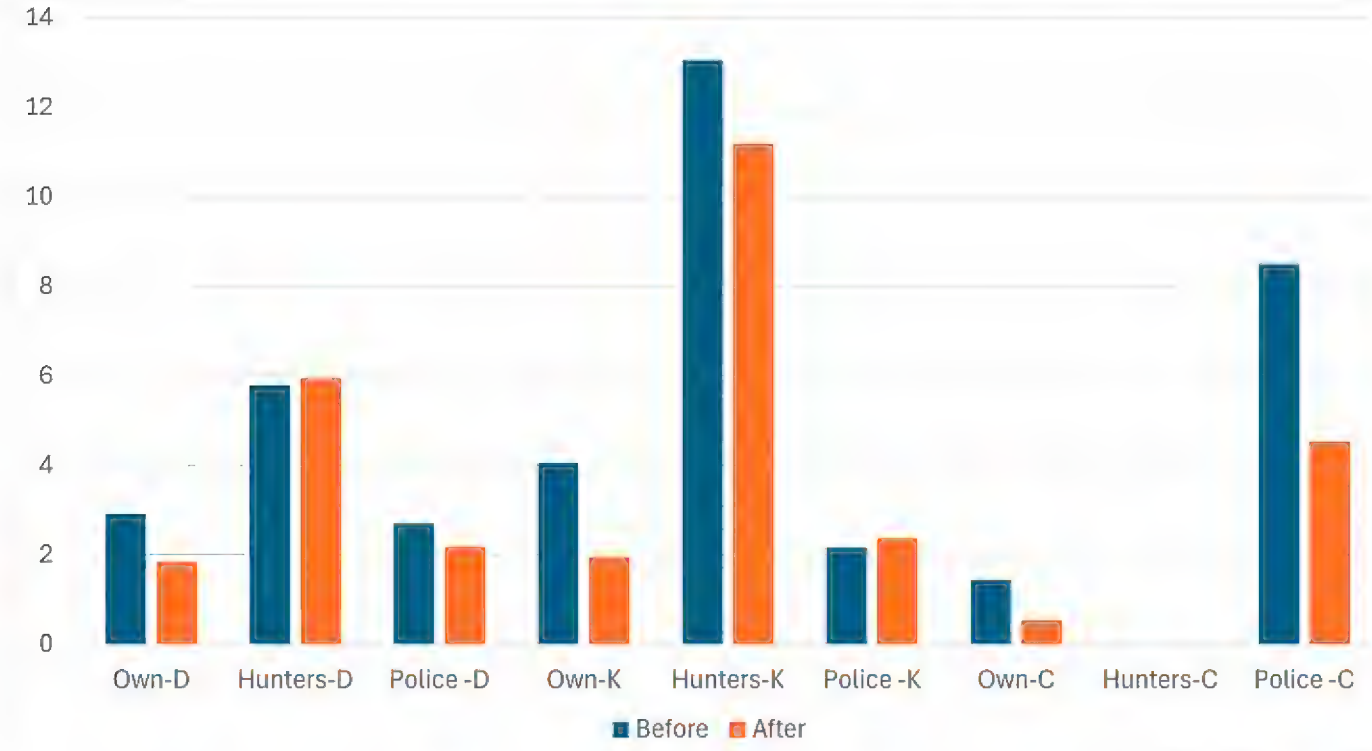

Figure 2. Comparison of average wildlife mortality by section type (D = Deter, K = Kombiset, C = Control) and data source Before and After deterrent installation.

As stated in the methodology, normality of the data was tested. However, due to the small sample size, it was not possible to reliably confirm deviations from normal distribution, and the results of these tests are therefore considered indicative only. For this reason, non-parametric methods were also applied to provide a more robust basis for interpretation.

Based on these data, the effect size metric *d* (Hedges' *d*) was calculated, which allows for comparing the strength of differences between the periods while taking into account variability and the number of observations. Table 4 presents these values for individual models and types of road sections.

Table 4. Mean values of effect size (Hedges' *d*) by model and section type (Deter, Kombiset, Control).

Mean Hedges' *d*	Model 1 O	Model 2 O+P	Model 3 O+H+P	Model 4 O&H&P	Model 5 O&P
D	-1.08	-0.96	1.7311	-1.4270	-0.9788
K	-3.06	-0.98	-0.7359	-1.1253	-1.3380
C	-1.58	-1.63	-1.6324	-2.1838	-2.1838

Table 4 shows the average values of the effect size metric *d* for each model. This metric represents the standardised mean difference (Hedges' *d*) between the period with installed deterrents and the period without them. It reflects both the magnitude of the difference in mortality and the variability and sample size within each group. The greater the absolute value of *d*, the more pronounced the effect in terms of reducing or increasing the number of wildlife-vehicle collisions after the installation of the devices. The data are categorised by section type (Deter, Kombiset, Control) and by individual analytical model.

A comparison of mean annual wildlife mortality per kilometre before and after the installation of deterrents showed a statistically significant difference.

The results of the test are presented in Table 5, which also includes the actual values of average mortality in the respective periods – that is, before (years 2022–2023) and after (years 2024–2025) the installation of the devices.

Mean annual wildlife mortality per kilometre decreased across all models and section types. Although all paired comparisons showed a reduction, only a small number reached statistical significance at $\alpha < 0.10$ (one Deter model, four Kombiset models, and one control model), reflecting the limited statistical power.

Table 5. Paired t-test results: mean annual mortality per kilometre Before and After deterrents installation (D-Deter, K-Kombiset, C-Control). Statistical significance ($\alpha < 0.10$) is highlighted by an asterisk.

	Model 1	Model 2	Model 3	Model 4	Model 5
D Before/After	2.92/2.17	5.37/4.02	10.89/9.96	3.8/3.32	2.8/2.01
D p-value	0.2499	0.1563	0.3801	0.2791	0.0722 *
K Before/After	4.05/2.31	5.97/4.29	18.52/15.47	6.42/5.16	3.1/2.14
K p-value	0.0699 *	0.0699 *	0.1638	0.0858 *	0.0916 *
C Before/After	1.44/0.53	9.52/5.07	9.52/5.07	4.97/2.54	4.97/2.54
C p-value	0.0546 *	0.153	0.153	0.1119	0.1119

Due to the limited sample size, the sign test was also applied for comparison. The results are presented in Table 6. This test allows a simple evaluation of whether the majority of changes between the before and after periods follow the same direction (e.g. a decrease). The table shows the number of negative changes relative to the total number of observations, along with statistical significance where applicable.

Statistically significant decreases were identified in two models for sections with the Kombiset deterrent and in three models for control sections. Following Table 7. shows the average percentage change in annual wildlife mortality per kilometre between the period before and after the installation of deterrents. The data are categorised by section type (Deter, Kombiset, Control) and by data source (own monitoring, hunting associations, Police).

From the presented data, the control sections show the highest decrease in mortality, and this pattern is consistent across the available data sources. In several cases, the decrease in control sections is more pronounced than in sections where deterrents were installed.

Table 6. Sign test: number of negative changes / total, by model and section type (Deter, Kombiset, Control). Asterisks indicate statistical significance levels: * $p < 0.10$, ** $p < 0.05$.

	Model 1	Model 2	Model 3	Model 4	Model 5
D	3/4	3/4	3/4	8/12	6/8
K	3/3 **	3/3 **	2/3	5/9	3/6
C	6/7 *	5/7	5/7	11/14 **	11/14 **

Table 7. Percentage change in annual wildlife mortality per one kilometre between Before and After periods.

	Deter	Kombiset	Control
Own	-36.86	-52.17	-62.86
Hunters	2.74	-14.27	NA
Police	-19.19	9.14	-46.6

Control-Impact (C-I) analysis

We compared the mean values of the effect size metric *d* using a series of parametric t-tests, the medians using the non-parametric Mann–Whitney U test, and additionally applied ANOVA across all three groups. However, none of these tests revealed any statistically significant differences between the groups (see Table 8).

For the Mann–Whitney U test, we report the test statistic (U) followed by the corresponding critical value at a significance level of $\alpha = 0.1$. This approach was chosen, because - for small sample sizes - exact p-values may not always be available or reliable, and the decision on significance is based on comparing the test statistic to a critical value.

For the t-tests and ANOVA, we report the p-values directly, as these tests are based on known parametric distributions under the null hypothesis. P-values are standard outputs in parametric testing and allow direct interpretation of significance relative to a chosen α level. None of the tests showed statistically significant differences between the groups at the $\alpha = 0.1$ level.

Table 8. Results of statistical tests comparing section types (C-I design): Mann–Whitney U, t-test and ANOVA, Deter, Kombiset, Control. Mann–Whitney U test values are presented as "U > critical value" at α = 0.1. T-tests and ANOVA show p-values. None of the comparisons were statistically significant at α = 0.1.

Test	Comparison	Model 1	Model 2	Model 3	Model 4	Model 5
Mann-Whitney U test	C-D	12 > 5	10 > 5	12 > 5	63 > 58	40 > 36
	C-K	8 > 4	8 > 4	5 > 4	44 > 41	44 > 25
	D-K	4 > 3	5 > 3	5 > 3	53 > 35	24 > 13
T-test (p-value)	C-D	0.3105	0.3003	0.1223	0.4608	0.4114
	C-K	0.1265	0.2921	0.2342	0.415	0.4881
	D-K	0.1525	0.4926	0.2895	0.4105	0.4176
ANOVA (p-value)	All groups	0.3665	0.7945	0.4189	0.8003	0.5954

In the following section, we evaluate the effect of deterrents compared to control sections using regression analysis. The dependent variable in all models is the effect size metric *d*, representing the standardized difference in wildlife mortality before and after the intervention.

The results of the regression analyses are presented in Table 9. For each model, the table shows the estimated intercept, which corresponds to the average value of the effect size metric *d* in control sections, along with the regression coefficients for the binary variables D and K. The corresponding p-values are included to evaluate statistical significance of each predictor. In addition, the R^2 values are reported to indicate the overall explanatory power of each model, i.e., the proportion of variance in *d* explained by the included predictors.

Table 9. Results of regression models comparing test and control sections. Asterisks indicate statistical significance level: ** p < 0.05.

	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept (Control)	-1.5763	-1.6324	-1.6324	-2.1838	-2.1838
D	0.4929	0.6743	3.3634	0.7569	1.205
K	-1.483	0.6483	0.8965	1.0585	0.8458
p-value Intercept	0.0407**	0.0362**	0.2946	0.0477**	0.007**
p-value D	0.6705	0.5645	0.1988	0.6311	0.3372
p-value K	0.2575	0.6142	0.7468	0.5368	0.5384
R^2	0.1668	0.0410	0.1463	0.0138	0.0406

The regression estimates suggest that the intercept is negative in all models and reaches statistical significance in four out of five cases (p < 0.05).

However, the coefficients for both explanatory variables D and K are statistically non-significant across all models, with p-values well above the standard significance threshold. Although the estimated coefficients are mostly positive, they are not statistically significant. Consequently, the results do not support the hypothesis that deterrent-equipped sections experienced a stronger reduction in mortality than control sections.

The reported R^2 values are relatively small, remaining below 0.1 in three of the five models.

Traffic intensity

Table 10 shows the results of traffic intensity monitoring in each section, including a comparison with the official traffic intensity determined during the national traffic census in 2020.

Traffic intensity fluctuates due to various external factors that affect the utilisation of individual sections. One possible factor contributing to traffic fluctuations is ongoing construction work on the road network, not only directly in the sections under investigation, but also in the surrounding sections, where delays due to limited traffic volume capacity force drivers to choose a different route than usual. This is the case with significantly reduced traffic volumes on section 7 (to approximately 60–65%), where construction work was carried out on the access routes to both end points of the section. On the other hand, Section 5 had a high comparative base from 2020, as it served as a detour route for one of the long-term closed sections at that time, and the measured intensity was around 70–80% of this base.

Table 10. Traffic intensity in each test section after recalculation to Annual Average Daily Traffic (vehicles/24 hours).

id	Road nr.	National Traffic Census 2020	May 2023	November 2023	May 2024	November 2024
1	I/34	6,980	6,055	5,845	5,717	5,916
2	I/34	11,513	13,620	12,926	11,199	12,885
3	II/112	4,104	2,473	3,007	3,426	3,131
4	I/19	8,424	8,033	8,182	8,415	8,202
5	II/602	4,594	3,492	3,885	4,518	3,900
6	II/602	14,248	14,316	14,882	15,951	15,685
7	I/38	9,732	5,875	5,758	6,357	6,251

Table 11 presents the results of correlation analyses between traffic intensity and animal mortality (or related metrics) for four different models: mortality before installation, mortality after installation, effect size (*d*) and percentage change in mortality.

Table 11. Correlation between traffic intensity and animal mortality metrics (Pearson correlation coefficient / Spearman rank correlation coefficient). Section type: D = Deter, K = Kombiset, data source: O = Own, H = Hunters, P = Police. Asterisks indicate statistical significance levels: * p < 0.10, ** p < 0.05, *** p < 0.01.

	Before	After	Effect size D	Percentage change in mortality %
All	0.03/-0.02	0.04/0.19	-0.03/0.06	-0.01/0.06
D	-0.26/-0.24	-0.3/-0.17	-0.01/-0.06	-0.08/-0.22
K	0.16/0.32	0.36/0.74**	0.14/0.37	0.44/0.42
O	0.04/0.14	0.84***/0.71**	0.44/0.39	0.76**/0.57*
H	0.12/0.11	0.01/0.18	-0.07/-0.18	-0.33/-0.21
P	-0.25/-0.11	-0.54/-0.18	-0.18/-0.25	-0.43/-0.68**

The correlation analysis suggests that, in most cases, the relationship between traffic intensity and animal mortality (or its derived metrics) appears weak or inconsistent. However, several statistically significant correlations were identified.

More pronounced and relatively consistent correlations were found in the own monitoring data. In the own monitoring data, traffic intensity after installation was positively correlated with mortality ($r = 0.84$, $p < 0.01$; Spearman $\rho = 0.71$, $p < 0.05$). The percentage change in mortality was also statistically associated with traffic intensity ($r = 0.76$, $p < 0.05$; $\rho = 0.57$, $p < 0.1$). These associations were observed within this subset of monitored sections.

In the Kombiset sections, a statistically significant positive correlation was identified for post-installation mortality ($\rho = 0.74$, $p < 0.05$). In the police dataset, a statistically significant negative correlation was identified between traffic intensity and the percentage change in mortality ($\rho = -0.68$, $p < 0.05$).

Discussion and conclusion

Our study aimed to verify the effectiveness of two types of combined optical-acoustic and optical-olfactory animal deterrents applying a BACI experimental design with unique above-standard length of continuous weekly data collection. The whole year round cadaver monitoring lasted for 21 months before installation of deterrents and 18 months after deterrents were mounted to the road poles. Moreover, we aimed to reflect the real practice, so we used all other available data such as the police database of collisions with wildlife or hunters' road mortality data and used them for further evaluation.

In spite of the long continuous monitoring period and widely recommended BACI study design, our presented results indicate that the installation of the devices itself did not have a decisive impact on reducing mortality and that the observed changes may have been influenced by other factors than the use of such technical mitigation measures (deterrent installation). In most cases, there was a decrease in animal mortality following the installation of deterrents, but this pattern had a weak statistical significance.

An interesting phenomenon that can be traced from our data is a statistically significant decrease in mortality in control sections, where deterrents were not installed. This finding suggests that there was a natural decrease in accidents involving mammals in the monitored region during the study period. This decrease was probably caused by other external influences that were not monitored, acting on a large landscape scale, such as natural fluctuations in the population size of selected species and their ecology and ethology, biorhythms (Kämmerle et al. 2017), crop distribution along roads (Madsen et al. 2002), road characteristics (Canal et al. 2018), weather conditions, the impact of disturbance, or other uncontrolled influences (Clevenger et al. 2015; Bartonička et al. 2018). There is no evidence of a sharp decline in the population size of local species, as the hunting rate of game species stayed at a similar level during the last two years (see Czech Statistical Office 2025). The impact of the data collection method can also be disregarded, as both our own data and the data collected by the police were consistent throughout the monitoring period (hunters did not collect data from the control sections).

One of the factors monitored was traffic intensity on the tested sections (B–A treatment). It was demonstrated that traffic intensity after installation showed a

strong positive correlation with mortality, and the percentage change in mortality was also significantly correlated with traffic based on our own mortality data set. These results suggest that traffic intensity may have had a measurable effect on mortality outcomes after the intervention in these monitored sections. However, the results of other studies examining the effect of traffic on mortality rates are mostly ambiguous and depend largely on the taxonomic group and specific species studied. According to studies reviewed by Pagany (2020), traffic had a predominantly positive effect on AVC (in 75%), meaning that the risk of AVC increases with increasing traffic volume, which is consistent with our findings.

The results of the deterrent effectiveness comparison suggest that during the period following the installation of deterrents, animal mortality decreased relatively more (by 21.9%) on road sections equipped with the Hagopur Kombiset than on road sections equipped with the Deer Deter deterrent (mortality reduction of 7.2%). However, the confidence interval is very wide and the result is therefore statistically insignificant (Table 3). In addition, our statistical evaluation recorded an even greater decline in mortality of 45.5% in the control sections, where deterrents were not installed. Therefore, while mortality declined overall, the results do not provide statistical support for attributing this decline specifically to the deterrent interventions. However, in sections where the Kombiset deterrent was installed, its effectiveness could be influenced by traffic intensity (Table 11).

Another reason for the observed ineffectiveness of the tested deterrents in reducing animal mortality could be the habituation to the light and sound stimuli of some species (Ujvári et al. 1998; Ujvári et al. 2004; D'Angelo et al. 2006). In two cases, hunters observed fallow deer and wild boars at night near test sections equipped with Deer Deter devices. The animals showed no signs of disturbance from the sound and light signals emitted by these devices while cars were passing by (Hejný, pers. comm.).

Limitations of the study

The lack of confirmed effectiveness of the tested deterrents may result from multiple interacting factors. Most importantly, it is uncertain whether animals respond to these deterrent stimuli at all, as no ethological validation of deterrents tested by us has been conducted. In the case of the Hagopur Kombiset, which combines a reflective component with an olfactory deterrent, previous studies indicate that the individual stimuli alone have not demonstrated sustained, statistically significant effects on wildlife behaviour or on reducing animal–vehicle collisions. Additional factors may include habituation to deterrent stimuli, seasonal or reproductive behaviours that override avoidance responses, individual variability in sensitivity, and competing environmental cues such as food odours or territorial scents. Collectively, these considerations underscore the challenges in achieving long-term, reliable deterrent effects in free-ranging wildlife.

The very low effectiveness of the Deer Deter device could be influenced by the fact that approximately 20% of the devices did not function properly during the night functionality checks and had to be replaced. One of the identified causes was insufficient battery charge in the devices. The deterrents are powered by a built-in battery that is recharged by a solar panel. However, in some cases—for example due to shading by vegetation, roads in cuttings, or improper panel orientation - sufficient charging did not occur, leading to device malfunctions.

This problem can be particularly significant during periods of short daylight hours (in winter) when solar charging is limited and on roads with high traffic intensity (device is in heavy, almost permanent use). Although technical shortcomings probably affected the overall effectiveness of the device, it is not possible to determine exactly to what extent these problems contributed to the low effectiveness observed. However, due to technical problems, the resulting effectiveness of the tested device cannot be attributed to the principle of its operation itself.

One of the main limitations of the study is the difference in data collection between the tested and control sections. In the test sections, data collection was carried out on foot throughout the study, whereas in the control sections, monitoring was carried out while driving slowly in a motor vehicle (scooter/car). This research setup could have influenced detectability. We tried to improve this disadvantage by extending the length of the control sections (4.7 times) in order to identify possible trends in mortality in the surrounding landscape. On both types of sections, we only recorded larger mammal species ranging in size from martens to ungulates, thereby attempting to minimize detection bias, as it is well known that smaller species or taxons (e.g. birds, amphibians) are more often overlooked when traveling by car (Teixeira et al. 2013; Santos et al. 2016).

It is important to note that for all individual data sources (O, H, P), the number of observations was limited to only 7 per model, which strongly limits the statistical power and increases the risk of type II errors (failing to detect real effects). Therefore, although some correlations reached significance, the results should be interpreted with caution, and further data collection is recommended to confirm identified trends.

From a statistical perspective, the limited number of observations also results in wide confidence intervals around the estimated effect sizes and regression coefficients, reflecting substantial uncertainty in the magnitude of the effects. In several models, the confidence intervals include both potentially meaningful reductions and negligible or even opposite effects. This imprecision limits the strength of inference and prevents firm conclusions regarding the true effectiveness or ineffectiveness of the tested deterrents. Consequently, the reported point estimates should be interpreted as indicative rather than definitive, and the absence of statistical significance should not be equated with evidence of no effect.

The observed effectiveness of the deterrents applies exclusively to the tested types from specific manufacturers and the overall landscape and traffic context, and cannot be generalized to other devices using the same principle of wildlife deterrence and other external conditions.

Recommendation

The tested deterrents showed no statistically significant effect in reducing mortality of selected wildlife groups on roads. Despite decades of use, it is striking how few studies have evaluated their real effectiveness in field conditions. It is time to stop trusting the testimonial reports from product manufacturers about the effects of their deterrents. In terms of financial costs, wildlife conservation, and human safety, this knowledge gap is concerning. Furthermore, it remains unclear whether animals respond to the deterrent stimuli employed in these specific devices. These findings underscore the urgent need for rigorous applied ethological research, the need for standard performance protocols, and

multi-site validation studies to ensure that only measures with proven efficacy are deployed on a larger scale along roads.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

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Author contributions

Conceptualization: VH. Data curation MK. Formal analysis: MK. Investigation: MSl. Methodology: JU, MSt, VH. Project administration: MSt. Supervision: VH. Writing – original draft: MSt. Writing – review & editing: ID, JU, MK, VH.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

References

Al Sayegh Petkovšek S, Kotnik K, Breznik K, Pokorny B (2025) Wildlife mortality on the Slovenian highways: monthly patterns, identification of hotspots and effectiveness of acoustic deterrents. Urban Ecosystems 28: 57. https://doi.org/10.1007/s11252-024-01616-z

Andreassen HP, Gundersen H, Storaas T (2005) The effect of scent-marking, forest clearing and supplemental feeding on moose–train collisions. Journal of Wildlife Management 69: 1125–1132. https://doi.org/10.2193/0022-541X(2005)069[1125:-TEOSFC]2.0.CO;2

Babińska-Werka J, Krauze-Gryz D, Wasilewski M, Jasińska K (2015) Effectiveness of an acoustic wildlife warning device using natural calls to reduce the risk of train collisions with animals. Transportation Research Part D: Transport and Environment 38: 6–14. https://doi.org/10.1016/j.trd.2015.04.021

Barrientos R, Ascensão F, D'Amico M, Grilo C, Pereira HM (2021) The lost road: do transportation networks imperil wild-life population persistence? Perspectives in Ecology and Conservation 19: 411–416. https://doi.org/10.1016/j.pecon.2021.07.004

Bartonička T, Andrášik R, Duľa M, Sedoník J, Bíl M (2018) Identification of Local Factors Causing Clustering of Animal-Vehicle Collisions. Journal of Wildlife Management 82(5): 940–947. https://doi.org/10.1002/jwmg.21467

Bartoš L (2018) TP 189 - Stanovení intenzit dopravy na pozemních komunikacích. Plzeň: EDIP, 73 pp. [in Czech]

Bartuška L, Biba V, Jeřábek K (2016) Verification of Methodical Procedure for Determining the Traffic Volumes Using Short-term Traffic Surveys. Procedia Engineering 161: 275–281. https://doi.org/10.1016/j.proeng.2016.08.553

Bíl M, Andrášik R, Janoška Z (2013) Identification of hazardous road locations of traffic accidents by means of kernel density estimation and cluster significance evaluation. Accident Analysis & Prevention 55: 265–273. https://doi.org/10.1016/j.aap.2013.03.003

Bíl M, Andrášik R, Bartonička T, Křivánková Z, Sedoník J (2018) An evaluation of odor repellent effectiveness in prevention of wildlife vehicle collisions. Journal of Environmental Management 205: 209–214. https://doi.org/10.1016/j.jenvman.2017.09.081

Bíl M, Andrášik R, Duľa M, Sedoník J (2019) On reliable identification of factors influencing wildlife-vehicle collisions along roads. Journal of Environmental Management 237: 297–304. https://doi.org/10.1016/j.jenvman.2019.02.076

Bíl M, Kušta T, Andrášik R, Cícha V, Brodská H, Ježek M, Keken Z (2020) No clear effect of odour repellents on roe deer behaviour in the vicinity of roads. Wildlife Biology 4: 1–11. https://doi.org/10.2981/wlb.00744

Bíl M, Sedoník J, Andrášik R, Kušta T, Keken Z (2024) Olfactory repellents decrease the number of ungulate-vehicle collisions on roads: Results of two-year carcass study. Journal of Environmental Management 365: 121561. https://doi.org/10.1016/j.jenvman.2024.121561

Bíl M, Balčiauskas L, Bílová M, Cellina S, Favilli F, Gačić D, Guinard E, Heurich M, Ivanova N, Junghardt J, Keuling O, Kruuse M, Kukalaj Q, Langbein J, Laube P, Licoppe A, Masaryk P, Maślanko W, Mayer M, Moroney A, Moţ R, Mrđenović D, Náhlik A, Nebunu A, Nezval V, Niemi M, Pokorny B, Psaralexi M, Ralevic S, Ricci S, Rolandsen CM, Rosell C, Santos SM, Seiler A, Steiner W, Swinnen KRR, Šprem N, Trajçe A, Trpeski V, van der Grift EA, Vogiatzakis I, Zihmanis I (2025) Wildlife-vehicle collision liability in Europe: A review of existing approaches and their implications. Journal of Environmental Management 380: 1–10. https://doi.org/10.1016/j.jenvman.2025.124986

Benten A, Annighöfer P, Torsten V (2018a) Wildlife Warning Reflectors Potential to Mitigate Wildlife-Vehicle Collisions: A Review on the Evaluation Methods. Frontiers in Ecology and Evolution 6: 1–12. https://doi.org/10.3389/fevo.2018.00037

Benten A, Hothorn T, Vor T, Ammer C (2018b) Wildlife warning reflectors do not mitigate wildlife–vehicle collisions on roads. Accident Analysis & Prevention 120: 64–73. https://doi.org/10.1016/j.aap.2018.08.003

Benten A, Balkenhol N, Vor T, Ammer C (2019) Wildlife warning reflectors do not alter the behavior of ungulates to reduce the risk of wildlife-vehicle collisions. European Journal of Wildlife Research 65(5): e76. https://doi.org/10.1007/s10344-019-1312-4

Botting I, Ascensão F, Navarro LM, Paniw M, Tablado Z, Román J, Revilla E, D'Amico M (2025) The road to success and the fences to be crossed: consideringmultiple infrastructure in landscape connectivity modelling. Wildlife Biology 2025(3): e01187. https://doi.org/10.1002/wlb3.01187

Brieger F, Hagen R, Vetter D, Dormann CF, Storch I (2016) Effectiveness of light-reflecting devices: A systematic reanalysis of animal-vehicle collision data. Accident Analysis and Prevention 97: 242–260. https://doi.org/10.1016/j.aap.2016.08.030

Brieger F, Hagen R, Kröschel M, Hartig F, Petersen I, Ortmann S, Suchant R (2017) Do roe deer react to wildlife warning reflectors? A test combining a controlled experiment with field observations. European Journal of Wildlife Research 63: 72. https://doi.org/10.1007/s10344-017-1130-5

Brieger F, Kämmerle J-L, Hagen R, Suchant R (2022) Behavioural reactions to oncoming vehicles as a crucial aspect of wildlife-vehicle collision risk in three common wildlife species. Accident Analysis & Prevention 168: 106564. https://doi.org/10.1016/j.aap.2021.106564

Burton JA, Cutler DF, Sherwood BR (2003) Wildlife and roads: The ecological impact. Imperial College Press, 316 pp.

Canal D, Camacho C, Martín B, de Lucas M, Ferrer M (2018) Magnitude, composition and spatiotemporal patterns of vertebrate roadkill at regional scales: A study in southern Spain. Animal Biodiversity and Conservation 41(2): 281–300. https://doi.org/10.32800/abc.2018.41.0281

Ceia-Hasse A, Navarro LM, Borda-de-Água L, Pereira HM (2018) Population persistence in landscapes fragmented byroads: disentangling isolation, mortality, and the effect of dispersal. Ecological Modelling 375: 45–53. https://doi.org/10.1016/j.ecolmodel.2018.01.021

Clevenger AP, Barrueto M, Gunson KE, Caryl FM, Ford AT (2015) Context-dependent effects on spatial variation in deer-vehicle collisions. Ecosphere 6(4): 47. https://doi.org/10.1890/ES14-00228.1

Czech Statistical Office (2025) Základní údaje o honitbách, stavu a lovu zvěře - od 1. 4. 2023 do 31. 3. 2024. https://csu.gov.cz/produkty/zakladni-udaje-o-honitbach-stavu-a-lovu-zvere-od-1-4-2023-do-31-3-2024 [Accessed on 11.06.2025]

D'Angelo GJ, D'Angelo JG, Gallagher GR, Osborn DA, Miller KV, Warren RJ (2006) Evaluation of wildlife warning reflectors for altering white-tailed deer behavior along roadways. Wildlife Society Bulletin 34: 1175–1183. https://doi.org/10.2193/0091-7648(2006)34[1175:EOWWRF]2.0.CO;2

Elmeros M, Winbladh JK, Andersen PN, Madsen AB, Christensen JT (2011) Effectiveness of odour repellents on red deer (Cervus elaphus) and roe deer (Capreolus capreolus): a field test. European Journal of Wildlife Research 57(6): 1223–1226. https://doi.org/10.1007/s10344-011-0517-y

Fahrig L, Rytwinski T (2009) Effects of roads on animal abundance: an empirical review and synthesis. Ecology and Society 14(1): 21. https://doi.org/10.5751/es-02815-140121

Faltusová M, Ježek M, Ševčík R, Silovský V, Cukor J (2024) Odor Fences Have No Effect on Wild Boar Movement and Home Range Size. Animals 14(17): 2556. https://doi.org/10.3390/ani14172556

Favilli F, Bíl M, Sedoník J, Andrášik R, Kasal P, Agreiter A, Streifeneder T (2018) Application of KDE+ software to identify collective risk hotspots of ungulate-vehicle collisions in

South Tyrol, Northern Italy. European Journal of Wildlife Research 64: 59. https://doi.org/10.1007/s10344-018-1214-x

Forman RTT, Alexander LE (1998) Roads and their major ecological effects. Annual Review of Ecology, Evolution and Systematics 29: 207–231. https://doi.org/10.1146/annurev.ecolsys.29.1.207

Generali Česká pojišťovna a CDV (2024) SRNA index: Počet srážek se zvěří i škody za ně rostou, nejvíce bouraček se přihodí za šera a v noci. https://www.generaliceska.cz/ [Accessed on 10.07.2025]

Grilo C, Koroleva E, Andrášik R, Bíl M, González-Suárez M (2020) Roadkill risk and population vulnerability in European birds and mammals. Frontiers in Ecology and the Environment 18(6): 323–328. https://doi.org/10.1002/fee.2216

Hedges LV, Olkin I (1985) Statistical Methods for Meta-analysis. Academic Press Orlando, 361 pp.

Hill JE, DeVault TL, Belant JL (2019) Cause-specific mortality of the worlds's terrestrial vertebrates. Global Ecology and Biogeography 28(5): 680–689. https://doi.org/10.1111/geb.12881

Husek J, Kvicerova J, Cukor J (2026) Spatio-temporal variation and factors affecting European hare (*Lepus europaeus*) road mortality: Landcover diversity as a remedy. Global Ecology and Conservation 65: e04013. https://doi.org/10.1016/j.gecco.2025.e04013

Iuell B, Bekker GJ, Cuperus R, Dufek J, Fry G, Nicka C, Hlaváč V, Keller V, Rosell C, Sangwine T, Tørsløv N, Wandall B le Maire [Eds] (2003) Wildlife and Traffic: A European Handbook for Identifying Conflicts and Designing Solutions; KNNV, Utrecht, The Netherlands.

Jandová V, Bucková M, Hegrová J, Dostál I, Huzlík J, Effenberger K, Ličbinský R (2020) The Relationship among Precipitation, Application of Salt in Winter Road Maintenance and the Quality of Waterways and Soil around Motorway. Water 12(8): 2206. https://doi.org/10.3390/w12082206

Jasińska K, Babińska-Werka J, Krauze-Gryz D (2022) A test of wildlife warning reflectors as a way to reduce risk of wildlife-train collisions. In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 303–316. https://doi.org/10.3897/natureconservation.47.73052

Karlson M, Seiler A, Mörtberg U (2017) The effect of fauna passages and landscape characteristics on barrier mitigation success. Ecological Engineering 105: 211–220. https://doi.org/10.1016/j.ecoleng.2017.04.059

Kämmerle J-L, Brieger F, Kröschel M, Hagen R, Storch I, Suchant R (2017) Temporal patterns in road crossing behaviour in roe deer (*Capreolus capreolus*) at sites with wildlife warning reflectors. PLoS ONE 12(9): e0184761. https://doi.org/10.1371/journal.pone.0184761

Kuipers KJJ, Hilbers JP, Garcia-Ulloa J, Graae BJ, May R, Verones F, Huijbregts MAJ, Schipper AM (2021) Habitat fragmentation amplifies threats from habitat loss to mammal diversity across the world's terrestrial ecoregions. One Earth 4(10): 1505–1513. https://doi.org/10.1016/j.oneear.2021.09.005

Kušta T, Keken Z, Ježek M, Kůta Z (2015) Effectiveness and costs of odor repellents in wildlife-vehicle collisions: A case study in Central Bohemia, Czech Republic. Transportation Research Part D: Transport and Environment 38: 1–5. https://doi.org/10.1016/j.trd.2015.04.017

Langbein J, Putman RJ, Pokorny B (2011) Road traffic accidents involving ungulates and available measures for mitigation. In: Putman RJ, Apollonio M, Andersen R (Eds) Ungulate Management in Europe: Problems and Practices. Cambridge University Press, Cambridge, UK, 215–259. https://doi.org/10.1017/cbo9780511974137.009

Livingston TD (2019) Wildlife Road Mortality Survey Methodologies [Master's thesis, The University of Texas Rio Grande Valley]. ScholarWorks @ UTRGV. https://scholarworks.utrgv.edu/etd/508

Madsen AB, Strandgaard H, Prang A (2002) Factors causing traffic killings of roe deer Capreolus capreolus in Denmark. Wildlife Biology 8(1): 55–61. https://doi.org/10.2981/wlb.2002.008

Medrano-Vizcaíno P, Grilo C, Silva Pinto FA, Carvalho WD, Melinski RD, Schultz ED, González-Suárez M (2022) Roadkill patterns in Latin American birds and mammals. Global Ecology and Biogeography 31(9): 1756–1783. https://doi.org/10.1111/geb.13557

Moore LJ, Petrovan SO, Bates AJ, Hicks HL, Baker PJ, Perkins SE, Yarnell RW (2023) Demographic effects of road mortality on mammalian populations: a systematic review. Biological Reviews 98: 1033–1050. https://doi.org/10.1111/brv.12942

Moulherat S, Pautrel L, Debat G, Etienne M-P, Gendron L, Hautière N, Tarel J-P, Testud G, Gimenez O (2024) Biodiversity monitoring with intelligent sensors: An integrated pipeline for mitigating animal-vehicle collisions. Nature Conservation 57: 103–124. https://doi.org/10.3897/natureconservation.57.108950

Multi Wildschutz Warner (2025) Multi Wildschutz Warner. https://www.wildwechsel-unfall-vermeiden.de/index.html [Accessed on 06.06.2025]

Pagany R (2020) Wildlife-vehicle collisions - Influencing factors, data collection and research methods. Biological Conservation 251: 108758. https://doi.org/10.1016/j.biocon.2020.108758

Papp CR, Dostál I, Hlaváč V, Berchi GM, Romportl D (2022) Rapid linear transport infrastructure development in the Carpathians: A major threat to the integrity of ecological connectivity for large carnivores. Nature Conservation 47: 35–63. https://doi.org/10.3897/natureconservation.47.71807

Portalnehod (2025) V Kraji Vysočina je podíl nehod způsobených střety se zvěří nejvyšší v rámci celé České republiky. https://portalnehod.cz/clanky/V-Kraji-Vysocina-je-podil-nehod-zpusobenych-strety-se-zveri-nejvyssi-v-ramci-cele-Ceske-republiky [Accessed on 10.06.2025]

Putman RJ (1997) Deer and road traffic accidents: options for management. Journal of Environmental Management 51(1): 43–57. https://doi.org/10.1006/jema.1997.0135

Putman RJ, Langbein J (2024) Deer Vehicle Collisions - a review of mitigation measures and their effectiveness. NatureScot Research Report 1354, 79 pp.

Regional Administration and Maintenance of Roads in Vysočina Region (2025) Regional Administration and Maintenance of Roads in Vysočina Region. https://www.ksusv.cz/silnicni-sit/ds-1064 [Accessed on 29.07.2025]

Remon J, Moulherat S, Cornuau JH, Gendron L, Richard M, Baguette M, Prunier JG (2022) Patterns of gene flow across multiple anthropogenic infrastructures: Insights from a multi-species approach. Landscape and Urban Planning 226: 104507. https://doi.org/10.1016/j.landurbplan.2022.104507

Roedenbeck IAE (2007) Landscape-scale effects of roads on wildlife. PhD Thesis, Justus-Liebig-Universität Giessen, Giessen, 156 pp.

Rutherford KL, St. Clair CC, Visscher DR (2025) Elk and Deer habituate to stationary deterrents in an agricultural landscape. Ecology and Evolution 15: e71752. https://doi.org/10.1002/ece3.71752

Rytwinski T, Fahrig L (2015) The impacts of roads and traffic on terrestrial animal populations. In: van der Ree R, Smith DJ, Grilo C (Eds) Handbook of road ecology, Wiley-Blackwell, UK, 237–246. https://doi.org/10.1002/9781118568170.ch28

Rytwinski T, van der Grift EA, Cunnington GM, Fahrig L, Findlay CS, Houlahan J, Jaeger JAG, Soanes K, van der Grift EA (2015) Experimental study designs to improve the evaluation of road mitigation measures for wildlife. Journal of Environmental Management 154: 48–64. https://doi.org/10.1016/j.jenvman.2015.01.048

Rytwinski T, Soanes K, Jaeger JA, Fahrig L, Findlay CS, Houlahan J, van der Ree R, van der Grift EA (2016) How effective is road mitigation at reducing road-kill? A meta-analysis. PLoS ONE 11(11): e0166941. https://doi.org/10.1371/journal.pone.0166941

Santos RAL, Santos SM, Santos-Reis M, Picanço de Figueiredo A, Bager A, Aguiar LMS, Ascensão F (2016) Carcass Persistence and Detectability: Reducing the Uncertainty Surrounding Wildlife-Vehicle Collision Surveys. PLoS ONE 11(11): e0165608. https://doi.org/10.1371/journal.pone.0165608

Snow NP, Porter WF, Williams DM (2015) Underreporting of wildlife-vehicle collisions does not hinder predictive models for large ungulates. Biological Conservation 181: 44–53. https://doi.org/10.1016/j.biocon.2014.10.030

Teixeira FZ, Coelho AVP, Esperandio IB & Kindel A (2013) Vertebrate road mortality estimates: Effects of sampling methods and carcass removal. Biological Conservation 157: 317–323. https://doi.org/10.1016/j.biocon.2012.09.006

Trombulak SC, Frissell CA (2000) Review of ecological effects of roads on terrestrial and aquatic communities. Conservation Biology 14: 18–30. https://doi.org/10.1046/j.1523-1739.2000.99084.x

Ujvári ML, Baagøe HJ, Madsen AB (1998) Effectiveness of wildlife warning reflectors in reducing deer-vehicle collisions: a behavioral study. Journal of Wildlife Management 62: 1094–1099. https://doi.org/10.2307/3802562

Ujvári ML, Baagøe HJ, Madsen AB (2004) Effectiveness of acoustic road markings in reducing deer-vehicle collisions: a behavioural study. Wildlife Biology 10: 155–159. https://doi.org/10.2981/wlb.2004.011

van der Ree R, Smith DJ, Grilo C (2015) The ecological effects of linear infrastructure and opportunities of rapid global growth. In: van de Ree R, Smith DJ, Grilo C (Eds) The handbook of road ecology, Wiley-Blackwell, UK, 1–9. https://doi.org/10.1002/9781118568170.ch1

Supplementary material 1

Overview of road sections on which AVC monitoring was carried out before and after (B-A) the installation of deterrents

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